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Estimating Costs and Effectiveness of Upgrades in Forestry Best Management Practices for Stream Crossings

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Abstract: Forestry Best Management Practices (BMPs) are used for protection of water quality at forest stream crossings, yet effects and costs for gradients of BMPs are not well documented. We evaluated forty-two truck road and skid trail stream crossings using three surrogates of BMP adequacy: (1) potential erosion rates for stream crossing approaches; (2) adequacy of stream crossing BMPs; and (3) overall BMP rating (BMP−, BMP-standard, and BMP+). Subsequently, BMP upgrades were recommended for enhancing BMP− or BMP-standard stream crossings. Costs for BMP upgrades were estimated using an existing road and skid trail cost method. The majority of truck road stream crossings were culverts, while skid trail stream crossings were primarily portable bridges. Potential erosion estimates, BMP audit scores, and BMP ratings all indicated that skid crossings have lower BMP implementation than truck road crossings. BMP improvements commonly identified for skid trail and truck crossings included addition of cover and water control structures. Improved BMPs at skid trail crossings were less expensive than those at truck road crossings. Current BMP guidelines provide economical and effective techniques for reducing erosion, and BMP upgrades have the potential to reduce erosion rates to similar levels found in undisturbed forests.

Keywords: forest roads; skid trails; erosion; best management practices; stream crossings; BMP costs

1. Introduction

1.1. Forest Roads, Erosion, and Sediment

Forest roads are necessary for permanent or temporary access for silvicultural forest operations [1,2]. However, forest roads have been associated with environmental problems in many timber producing regions [3]. Soil erosion and potential for sediment contributions to streams are common concerns associated with poorly designed, constructed, or maintained forest roads [4–6].

Erosion from forest roads is governed by numerous factors. Natural site factors, including precipitation, topography, and soils, cannot feasibly be altered, but should be considered during preharvest planning [7,8]. Anthropogenic factors related to road construction and management are more readily manipulated. The literature provides considerable insight regarding erosion and sedimentation consequences of road location [9–11], road grade [12–14], road density [15], road area [16,17], road infiltration rates [18], road surfacing conditions [19,20], traffic levels [5], expected road duration of use [21], road templates including cut and fill slopes [22,23], adequacy of drainage structures [24], and road connectivity to streams [25,26]. These considerations capture the challenges addressed by forest road and skid trail best management practices (BMPs).

Best management practices (BMPs) are methods and techniques used to minimize soil erosion and sedimentation from forest operations [7]. Typical methods of erosion minimization involve control of quantity and velocity of water on road surfaces, location of roads on desirable grades and terrain, provision of adequate road drainage and road cover, control of traffic, maintenance of permanent roads, closure of temporary roads, and design of appropriate stream crossings [10,27–31].

The widespread application of and reliance on forest road BMPs is supported by the literature from many wood-producing regions, which clearly shows that poorly planned or executed roads can cause erosion and sediment problems, even though these areas often comprise less than 10% of the harvest area. Germain and Munsell [17] evaluated 43 hardwood harvest sites in New York and found that the average area of road and skid trails in harvest sites was between 3% and 13%, but they attributed 90% of the erosion to the transportation areas.

Megahan and Kidd [32] evaluated a dense network of logging roads on steep terrain in Idaho where 25% of the area was comprised of mobile yarder (Jammer) trails located approximately 120 m apart. The roads increased erosion rates 750-fold compared to non-harvested areas. Motha *et al.* [33] examined managed *Eucalyptus* stands in Australia. They found that graveled forest roads and non-graveled decks and skid trails comprised less than 3% of the area, but disproportionately contributed between 6% and 25% of stream sediment. Roads produced 10 times more sediment per unit area than harvested areas and 20 to 60 times more sediment than non-disturbed forests. Croke and Mockler [34] determined that 35% of a 75-km road network in Australia was directly or partially linked to streams by road cross drains and stream crossings.

Worrell *et al.* [35] modeled erosion rates for both ground-based skidding with bladed skid trails and cable yarding harvests in hardwood forests in the rugged Virginia Appalachian Plateau region. For three tracts having ground-based harvesting, bladed skid trails were estimated to produce 71% of the total erosion associated with the harvests, although the skid trails comprised only 7.7% of the harvest area. Within three cable yarder harvests, roads, decks, and skid trails between the yarder landing and truck loading deck produced 34% of the total harvest erosion, even though they accounted for only 4.4% of the area.

Wemple *et al.* [36] examined two watersheds dominated by Douglas fir in the Cascade Mountains in the U.S. Pacific Northwest region and found forest roads to be associated with 44% of 80 sediment debris slides, even though roads comprised only 3.1% of the area. Sidle *et al.* [37] provided a sediment budget for a harvested area in tropical Malaysia, where poorly planned roads and skid trails were constructed on steep terrain with little attempt to apply BMPs. Roads and skid trails accounted for 11.2% of the harvest area. The roads were more directly connected to streams than the skid trails, and 78% of the eroded soil from roads reached the streams, whereas 21% of eroded material from skid trails reached the streams. The researchers concluded that application of standard BMPs was the best approach to reducing erosion and sediment delivery rates.

Aust and Blinn [7] summarized the findings from over 50 research studies regarding water quality associated with forest operations. They concluded that "most water quality problems associated with forest harvesting are problems caused by poorly designed and constructed roads and skid trails".

1.2. Stream Crossings

Within the road network, multiple researchers have concluded that stream crossings on road and skid trail segments have disproportionately high potentials to introduce sediment into stream [27,38–40]. Taylor *et al.* [41] reviewed the literature regarding forest stream crossings and sediment and concluded, "forest stream crossings are a major sediment source in forest streams because crossings serve as focal points for introducing sediment-laden runoff into streams".

Croke *et al.* [40] found that road and ditch networks increase direct connectivity of forest roads to streams. In addition, several researchers [42–44] concluded that road stream crossings can compromise the sediment trapping ability of streamside management zones.

1.3. Forestry BMPs and Roads

While previous research clearly supports the premise that forest roads and stream crossings with inadequate or poorly implemented BMPs can accelerate soil erosion and, potentially, sedimentation, numerous research reviews have concluded that BMPs [4,7,45–47], minimum standard roads [48] low-impact harvesting [49], reduced-impact logging [50], or similar techniques can be used to reduce soil erosion and sedimentation. Following the passage of the Federal Water Pollution Control Act of 1972, state forestry agencies developed Forestry BMPs [45,46] specifically designed to minimize the erosion and sediment associated with forest operations with major emphases on forest roads, skid trails, and stream crossings [7,45–47,51,52].

Stuart and Edwards [18] emphasized that BMPs are based on established physical relationships so that BMPs remain relevant over the passage of time. Kochenderfer *et al.* [53] examined sediment export from a West Virginia forest harvest that included roads in order to test the efficacy of West Virginia's BMPs. They concluded that forestry BMPs were effective for sediment protection and that sediment levels returned to preharvest levels within three years of harvest. Litschert and MacDonald [25] examined sediment linkages with 200 harvest sites in the Sierra Nevada and Cascade Mountains of California and found only six sediment linkages (five from skid trails). They attributed the remarkably small number of sediment linkages to the increased use and refinement of forestry BMPs and silvicultural techniques. Harris *et al.* [54] examined the effects of upgrading poorly designed stream crossings to improved stream crossings and BMPs for 30 commercial timberland stream crossings in northwestern California. They concluded that the enhanced stream crossings produced little sediment and that improved stream crossings could significantly reduce sediment contributions from forest roads.

Madej [55] compared the effects of road closure and use of BMPs on sediment delivery. Roads receiving treatment with BMPs produced 10–550 m^3 of sediment per km of road, whereas the roads with no BMPs produced 1500–4700 m^3 per km of road. They concluded that the road removal/closure BMPs substantially reduced sediment produced by forest roads. Wear *et al.* [56] examined daily total suspended sediment above and below nine operational stream crossings (temporary skidder bridges) to determine the influence of a range of BMPs used for closing temporary skidder stream crossing approaches in the Piedmont region. Overall, they found that the use of either logging debris (slash) or seed with straw mulch was highly effective for controlling sediment contributions from such crossings.

Wade *et al.* [57] and Sawyers *et al.* [58] conducted companion studies that evaluated BMPs for closing bladed and overland skid trails in the Piedmont region. Both studies found that slash and mulch with seed were highly effective treatments for skid trail closure and erosion control. The mulch with seed BMP practice reduced erosion by 46-fold on the bladed skid trail and by 7.4-fold on the overland skid trail. Slash treatments reduced erosion by 19-fold and 4.6-fold on bladed trails and overland trails, respectively.

Brown *et al.* [16] compared sediment production on nine forest truck road stream crossing approaches in the Virginia Piedmont that received either gravel or no-gravel BMP treatments. The roads receiving gravel treatments had sediment delivery rates of 10–16 $Mg \cdot ha^{-1} \cdot year^{-1}$, while the bare soil treatments produced 34 to 287 $Mg \cdot ha^{-1} \cdot year^{-1}$. They concluded that the gravel BMP treatment could reduce sediment production for stream crossings by 7.5-fold. Brown *et al.* [19] compared different levels of gravel applications to stream crossing approaches as a BMP for control of stream sedimentation in a rainfall simulation experiment in the Piedmont of Virginia. Gravelling 50% and 100% of stream crossing approaches resulted in 2-fold and 10-fold reductions of median stream sediment when compared to the bare soil control approaches.

A summary of the literature indicates that forest roads, particularly the road segments at stream crossings, can contribute significant amounts of sediment to streams, but careful application of forest BMPs can prevent or minimize sedimentation. Since 1972, BMP compliance rates have consistently improved [45], and the 2014 national average for BMP compliance was approximately 92% [59]. However, efforts to consider additional BMPs may be justified. Several Federal Circuit Court cases and a recent U.S. Supreme Court case considered changing the nonpoint source pollution status of forest roads and stream crossings [60,61]. Additionally, the USEPA has recently announced the Clean Water Rule, which will potentially change the scope of wetland regulations for smaller streams [62]. Clearly, it would be beneficial to evaluate the potential for enhanced BMPs for stream crossings, but it is also important to consider the costs of such improvements in order to best utilize limited resources to maximize results [48,63–65]. Furthermore, Anderson and Lockaby [51] evaluated research gaps involving forest operations and sediment production and concluded that five of the nine major research gaps specifically involved the lack of information regarding sediment delivery from forest roads having different levels of BMPs.

2. Objectives

The research presented in this manuscript was developed with the overall goal of evaluating potential sediment production and solutions for stream crossings in the Piedmont region. However, due to the similarity in BMPs for a variety of land uses and regions, we also believe that our findings will have potential application in other geographical areas and land uses. Specific objectives were to: (1) compare estimated annual erosion rates for skid trail and truck road crossings; (2) identify specific erosion problems that needed to be addressed at the crossings; (3) propose specific BMP improvements to reduce erosion; and (4) calculate the costs associated with improving BMPs.

3. Materials and Methods

3.1. Study Sites

The southern Piedmont region of Virginia was selected for study (Figure 1) because this major wood-producing region is an area of intense forest operations that represents sites ranging from Alabama through Virginia [66]. The Piedmont has rolling terrain, and many of the current forests are former agricultural fields that were converted from forest land to field between the late 1700s and middle 1800s. Massive erosion associated with poor agricultural practices and socio-economic factors contributed to agricultural abandonment in the late 1800s through mid-1900s [67,68]. Current forests are typically dominated by loblolly pine (*Pinus taeda* L.) plantations or naturally regenerated stands of Virginia pine (*Pinus virginiana* Mill.) and upland hardwoods on abandoned fields. Stream floodplains are dominated by species such as yellow poplar (*Liriodendron tulipifera* L.), sweetgum (*Liquidambar styraciflua* L.), and red maple (*Acer rubrum* L.) [69]. The majority of timber harvests are mechanized operations primarily involving the use of wheeled feller-bunchers and rubber-tired grapple skidders. Many loggers own small bulldozers for road work and BMP installation and conduct both the road construction and BMPs [70]. Typically, some BMPs are used pre harvest (e.g., marking streamside management zones), some BMPs are used during harvest (e.g., water control structures), and some BMPs are used only after harvest completion (e.g., water bars on skid trails).

Timber harvesting contractors are required to notify the Virginia Department of Forestry (VDOF) within three working days after harvesting begins so that sites can be inspected for compliance with the Virginia Silvicultural Water Quality Law [71]. VDOF personnel maintain a database of all harvests: thus, we requested that the VDOF use their database management system to develop a list of timber harvest sites with the following criteria:

(1) Only Piedmont sites that had been harvested within the preceding four months were eligible for selection, because this allowed us to examine the sites during the more erosive phase immediately after harvesting.
(2) In order to minimize travel, sites were selected from 13 counties that comprise the southern Piedmont physiographic region of Virginia.
(3) Tract areas were required to be ⩾8 ha (⩾20 acres), which generally represents the minimal size of conventional harvests.These requirements generated 340 potential sites, onto which we subsequently imposed additional restrictions:
(4) All harvested tracts were required to have at least one stream crossing.
(5) Only harvests conducted for silvicultural purposes were included in order to exclude land use conversion operations.
(6) Sites having unusual or non-representative features were eliminated.

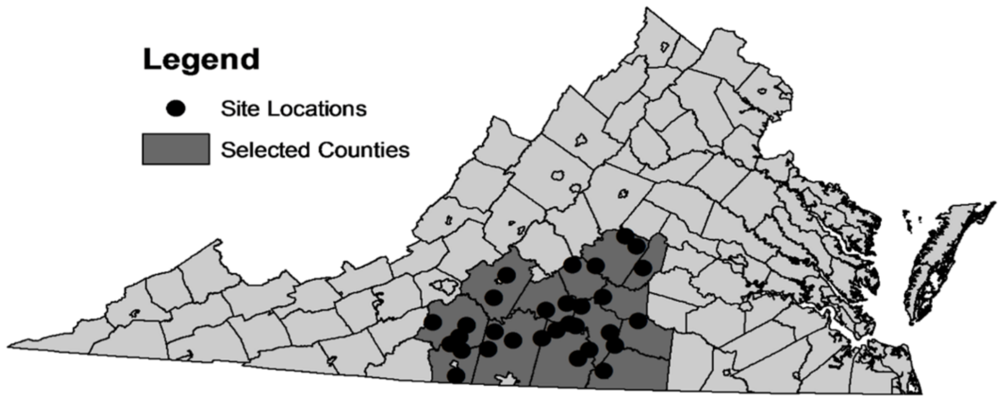

Figure 1. General location of the 30 harvest sites containing 20 truck road stream crossings and 22 skid trail stream crossings in the southern Piedmont region of Virginia. Map is not to scale.

Sites were categorized based on stream crossing type (truck road or skid trail crossings) and permanence of the crossings (*i.e.*, temporary vs permanent) because both of these factors have been found to be related to erosion rates [5,25]. Individual numbers were assigned to all sites and a random number generator was used to randomly select 30 sites from each stream crossing category (truck road or skid trail). Landowners of selected sites were contacted in order to gain access permission, with the original goal of acquiring a minimum of 10 sites for both truck and skidder categories.

3.2. Field Measurements

Field data collection occurred in summer 2014 at 22 skid trail and 20 truck road stream crossings and approaches located on 30 tracts (Figure 1), which represented approximately 9% of the total harvests in the region during that period. For each of the 42 crossings, both approaches were evaluated independently and then a weighted average was developed for each individual stream crossing based on the area of the two stream crossing approaches. An average potential soil erosion rate, BMP audit score, BMP classification rating, estimated effects of BMP enhancement, and overall BMP enhancement costs were estimated for each individual stream crossing. General information collected for each road or skid trail crossing included stream crossing width, culvert diameter, slope shape of the stream crossing approach (e.g., convex), road design (engineered, legacy, non-engineered), and road template (insloped, outsloped, cut and fill slope characteristics). The approaches and crossings were photographed from six directions to allow further post hoc examinations and analysis.

3.3. Stream Crossing Sediment Evaluation

Conditions of the stream crossings relating to potential stream sedimentation were evaluated with three different techniques: (1) modelled potential soil erosion estimates; (2) percentage of positive responses to the Virginia BMP audit questionnaire; and (3) an overall stream crossing BMP compliance rating based on condition and adequacy of the road template, cover, drainage, and stream crossing structures as compared to the VDOF BMP guidelines.

3.4. Soil Erosion Model

Potential soil erosion was estimated for each crossing approach using the Universal Soil Loss Equation as modified for forestland (USLE-Forest) [72]. Christopher and Visser [73] advocated use of the USLE-Forest methodology for evaluating the adequacy of forestry BMPs, and several researchers have found that the model compares favorably with direct measures of soil erosion for both roads [16,74] and skid trails [58,75] in the Piedmont region. Egan [76] emphasized that the USLE-Forest is particularly useful for evaluating road and stream crossing BMPs because data collection for model parameterization focuses the reviewer on site attributes that are often addressed by forestry BMPs.

The USLE-Forest requires the following site-specific data to predict long-term average soil losses resulting from sheet and rill erosion: long-term rainfall averages, soil erodibility values determined by the Natural Resource Conservation Service (NRCS) for a given soil series, and factors for slope length and steepness, soil cover, and management practices. The USLE equation is described below [72]:

$$A = R \times K \times LS \times CP$$

where A is soil loss per unit area, R is the rainfall and runoff factor, K is the soil erodibility factor, LS is the slope-length factor, and CP is the cover and management factor (including bare soil, residual binding, soil reconsolidation, mean canopy height and cover, stepped topography, onsite storage, vegetation).

R-values for the Piedmont were selected from the rainfall index erosivity map in the USLE-forest manual [72]. Due to their close proximity, R-values were the same for all 42 sites, so precipitation differences were held constant for our evaluation of erosion potential. This also signifies that soil erosion estimates are influenced more strongly by site and anthropogenic factors.

Stream crossings were geo-referenced with a recreational-grade GPS unit and the soil series corresponding to the appropriate soil horizon was determined with the Web Soil Survey [77]. Subsequently, field estimates of soil texture [77] from the appropriate soil horizon were compared to the NRCS Web soil textures and appropriate K values were chosen.

Stream crossing approach lengths were determined as the distance between the nearest upslope water control structure (*i.e.*, water bar and/or water turnout) and the stream bank (Figure 2). If no water control structures were present, approach length was measured to the most distant point where the road was no longer contributing water to the stream. The road approach slope was measured with a hand clinometer to the nearest 1% slope. LS factors were determined by using the provided LS values in the USLE-forest manual [72].

The C values were determined using sub-factors for disturbed soils. Subfactors considered included bare soil percent and residual binding effects, canopy percent over bare soil, steps, on-site storage, and vegetation effects related to erosion control. Surface cover and bare soil were estimated by walking in a zigzag pattern for multiple passes along the running surface for the entire length of the stream crossing approaches and counting the number of footsteps where the toe of the boot fell upon covered or bare soil (*i.e.*, ("covered" steps/total steps) $\times$ 100 = percent surface cover). Canopy cover was estimated with a spherical densitometer to the nearest 1%. On-site storage was based on the selection criteria provided in the USLE-Forest manual and step effects were estimated after visual examination. The importance of invading vegetation was based on the native or planted vegetation on the sites.

The USLE-Forest equation is calculated in tons $ac^{-1}\cdot year^{-1}$, which we converted to $Mg\cdot ha^{-1}\cdot year^{-1}$. In order to compare potential erosion rates from specific crossings, erosion rates were converted into $Mg\cdot crossing^{-1}\cdot year^{-1}$ by dividing the erosion rate by the crossing approach area. Erosion estimates for stream crossing approaches were assumed to be equivalent to sediment delivery due to the direct proximity of runoff to the stream [16].

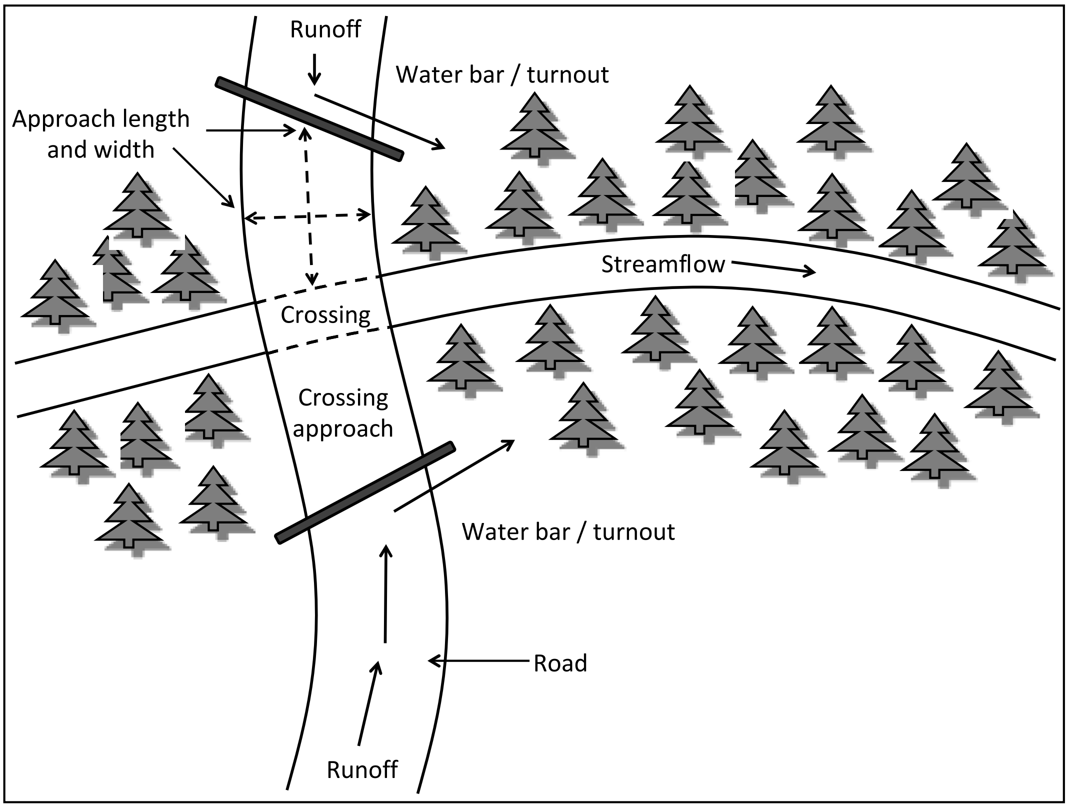

Figure 2. Plan view of an idealized stream crossing.

3.5. BMP Audit Scores

BMP audit reports are used to compare the adequacy of BMP implementation [78] and have sometimes been used as surrogates for BMP effectiveness [17,79,80]. The VDOF BMP audit utilizes the protocol proposed by the Southern Group of State Foresters [81] and evaluates BMP implementation in 10 categories [82]. Virginia has two levels of BMP inspections, a simplified inspection that is conducted on every harvesting site by local VDOF water quality staff and a complex "audit" inspection form that is performed on 240 sites per year by departmental water quality specialists [83]. For our examinations we answered subsets of the BMP audit questions that addressed roads (19 questions), skid trails (13 questions), and stream or wetland crossings (19 questions), and ignored non-relevant categories such as site preparation. In instances where a particular question was not applicable to a specific stream crossing approach, the question was not included. BMP audit scores represent the percent of applicable questions answered "Yes" for each category (e.g., roads, stream crossings) being evaluated. An overall BMP audit score was calculated for each site based upon the individual audit scores for roads, skid trails, stream crossings, and streamside management zones (SMZs) at the crossings.

3.6. BMP Guideline Ratings

At each stream crossing, information was collected in order to rate the overall BMP implementation. Overall ratings were based on VDOF guidelines [71] for condition and adequacy of the road sub-categories (road template, water control, surface cover, and stream crossing structures) (Table 1). Each sub-category received a rating of BMP−, BMP-standard, or BMP+. The road template sub-category was not applicable for skid trails. The sub-category ratings were used to assign an overall site rating of BMP−, BMP-standard, or BMP+, similar to the BMP categories used by Morris *et al.* [84]. The overall BMP rating was based on the majority of the sub-category ratings. For example, a skid trail with a water control rating of BMP+, surface cover rating of BMP-standard, and stream crossing structure rating of BMP+, would receive an overall rating of BMP+. For questionable or borderline sites, the final decision regarding BMP level was made by two professional foresters having research expertise in forest roads and water quality issues following a reexamination of questionable features and the six photos taken at each stream crossing.

Table 1. Sub-categories included in the overall rating of existing BMP implementation at each site based on the Virginia Department of Forestry (VDOF) Best Management Practices (BMP) manual criteria [71].

Category	Evaluation Criteria
Road template	Is the road entrenched? Does the road template (insloped, outsloped, crowned) shed water from the road surface in minimal amounts?
Water control	Are water control structures spaced adequately based on road grade? Do water control structures reduce rill formation by redirecting surface runoff from the road surface in small amounts? Do water control structures redirect surface runoff away from the stream?
Surface cover	To what extent does surface cover reduce the impacts of inter-rill (raindrop splash and sheet-flow) and rill (concentrated overland flow) erosion?
Stream crossing	Is the stream crossing location favorable for gentle approaches, stable stream banks, crossing at a 90° angle, and/or avoiding excessive fill? Did temporary crossing structures protect the stream channel and stream banks from skidding? Is culvert fill sufficient to withstand expected traffic volumes and loads? Is the culvert diameter sufficient for water conveyance during storm events? Does the culvert obstruct streamflow due to blockage by debris and/or sediment? Does the culvert impede fish passage?

3.7. Predicting Effects of BMP Enhancements

Subsequent to the stream crossing condition evaluations, BMPs that were needed to improve stream crossing approaches were considered. BMPs were suggested for all crossings having overall inadequate BMP implementation (BMP−), and standard BMPs (BMP-standard) in order to hypothetically adjust the BMP implementation to the next highest level of BMP compliance. Since major reconstruction of the road template would cause additional disturbance of the surface soil and potentially more sediment delivery to the stream, we did not consider changes to improve the road template ratings or road relocation, as this type of relocation and redesign was beyond the scope of the study. However, for the surface cover, water control, and crossing structures sub-categories, we considered BMP options that could feasibly increase BMP− ratings to BMP-standard, and BMP-standard to BMP+ based on the VDOF technical manual of recommended forestry BMPs [71]. For example, slope and length of the stream crossing approaches were compared with the recommended spacing of water control structures (based on slope percent) for roads and skid trails. If the spacing of water control structures was inadequate, we proposed additional water control structures to satisfy the VDOF BMP guidelines. In addition, when water control structures met the standards, but we wanted to improve the ratings to BMP+, we identified feasible and appropriate improvement techniques, such as adding hay bales in road ditches, silt fences, and/or improving ditch turnouts. The actual stream crossing structures were rarely an erosion problem at the sites we visited, but BMPs were identified to potentially improve those crossings having problems such as eroding fill, plugged structures, and rutted crossings.

The VDOF technical manual [71] does not provide specific guidelines regarding the extent of surface cover on stream crossing approaches. We calculated mean surface cover by road type for sites that had BMP-standard and BMP+ surface cover ratings. These averages provided a benchmark for the percent surface cover of sites with BMP− and BMP-standard surface cover ratings (e.g., BMP− was improved to BMP-standard and BMP-standard was improved to BMP+). The proposed improvements were determined by adjusting the BMP practices already used on the site. For example, if gravel was being used for cover, but erosion control was inadequate, we considered the addition of more gravel. Where water bars were being used for water control, then sufficient numbers of water bars were proposed as necessary. Erosion rates were then determined a second time after hypothetical BMP improvements as the BMP enhancements reduced slope distances and increased cover percentages.

3.8. Cost Estimates for Improved BMPs

After hypothetical BMP enhancement, we used the average costs presented in the Virginia Tech Road and Skid Trail Cost Method [85] to estimate the costs associated with the BMP improvements. This procedure has been compared to actual costs on several roads and typically provides estimates within 10% of actual costs.

For our cost estimates we followed the BMP already in use, so typically, logging slash was used for cover on skid trails, while gravel was considered for cover on truck roads. Costs for additional slash application ($0.35 m^{-2}) were based on Sawyers *et al.* [58], and delivered gravel costs were based on average local quarry estimates of $22.73/Mg ($25/ton). For gravel cover, we multiplied the additional area of cover (m^2) by a mean gravel depth of 10 cm [71]. Gravel volumes were converted to mass by assuming a gravel bulk density of 1604 $kg \cdot m^{-3}$ [86].

3.9. Statistical Analysis

Data were collected from recently closed forest operations and were not suitable for comparison as a designed experiment. Rather, data were categorized primarily by type of crossing (truck road *vs.* skid trail) and descriptive statistics were used to explain findings. The majority of the data were ordinal in nature rather than nominal, so means, medians, and maximum and minimum values are the standard patterns of presentation [87]. All statistical evaluations were performed using the statistical software JMP [88].

4. Results

The 42 stream crossings had four types of stream crossing structures: culverts (42.8%), portable bridges (42.8%), permanent bridges (4.8%), and pole crossings (9.6%) (Table 2). No fords were used for any of the observed crossings. The stream crossing type varied with the intended traffic. Permanent and temporary truck roads primarily used culvert stream crossings (88.2% and 66.7%, respectively). Temporary skidder crossings were dominated by portable bridge crossings (77.3%). Pole crossings were only used on temporary skid trail crossings.

Table 2. Number and percentage of stream crossing types found on permanent and temporary truck roads and temporary skid trails in the Virginia Piedmont.

Crossing Structure	Truck Road Permanent		Truck Road Temporary		Skid Trail Temporary	
	n	%	n	%	n	%
Culvert	15	88.2	2	66.7	1	4.5
Bridge (permanent)	2	11.8	-	-	-	-
Bridge (portable)	-	-	1	33.3	17	77.3
Pole Crossing	-	-	-	-	4	18.2
Total	**17**	**100**	**3**	**100**	**22**	**100**

BMP Quality

We evaluated and compiled the BMP audit scores, potential erosion rates, and potential sediment delivery (Table 3). Truck crossings had higher mean and median BMP audit scores (85.4% and 91.4%, respectively) compared to mean and median BMP audit scores for the skidder stream crossings (70.8% and 77.8%, respectively). For the same general period the VDOF 2014 BMP audit report [82] provided a somewhat similar mean BMP audit score for both truck and skid trail stream crossings in the central region (primarily Piedmont) of 89.2% overall. Truck approaches had lower potential erosion rates (11.9 $Mg \cdot ha^{-1} \cdot year^{-1}$) than the skidder stream crossing approaches (24.2 $Mg \cdot ha^{-1} \cdot year^{-1}$). Similar trends were observed for both crossing types when potential erosion was adjusted to represent potential erosion for the actual crossing size rather than a fixed area (Table 3).

Table 3. Descriptive statistics for the BMP audit scores, potential erosion rates, and potential sediment delivery per crossing for truck and skid trail stream crossings in the Piedmont Region.

Crossing Type	BMP Surrogate	n	Mean	Median	Min.	Max.
Truck	BMP audit score (%)	20	85.4	91.4	43.0	100.0
Skid	BMP audit score (%)	22	70.8	77.8	11.0	100.0
Truck	Potential erosion rate ($Mg \cdot ha^{-1} \cdot year^{-1}$)	20	11.9	6.3	<0.1	7.0
Skid	Potential erosion rate ($Mg \cdot ha^{-1} \cdot year^{-1}$)	22	24.2	9.6	<0.1	148.2
Truck	Potential erosion delivery per crossing per year ($Mg \cdot crossing^{-1} \cdot year^{-1}$)	20	0.7	0.4	<0.1	3.8
Skid	Potential erosion delivery per crossing per year ($Mg \cdot crossing^{-1} \cdot year^{-1}$)	22	1.8	0.4	<0.1	13.2

The third rating of stream crossings and BMP quality involved evaluation of the road template, drainage structure, cover BMPs, and stream crossing structure in order to develop an overall rating of the crossing and approaches (Table 4). The majority of the truck road crossings (55%) and skid trail crossings (45.5%) were rated BMP-standard. Stream crossing BMPs were typically less implemented on skid trail crossings than on road stream crossings; thus, the BMP− category was more common on skid trail crossings (31.8%) than on truck road crossings (15%). Overall, the BMP− category represented 23.8% of the total roads and skid trails. Mean BMP audit scores were lower for skid trail than for truck crossings for the three levels of BMPs, with BMP− having lower means (58% truck, 43.9% skid) and BMP+ having higher means (98.4% truck, 96.7% skid). Representative photographs of the three levels of BMP ratings and crossing types are presented in Figure 3.

Table 4. BMP guideline score for truck road stream crossings and skid trail stream crossings by BMP guideline compliance categorization.

Number and Percentages of BMP Variables	Truck BMP−	Truck BMP-Standard	Truck BMP+	Skid BMP−	Skid BMP-Standard	Skid BMP+
n	3	11	6	7	10	5
Relative frequency (%) of BMP guideline category	15	55	30	31.8	45.5	22.7
Mean compliance % BMP guideline	58.0	85.8	98.4	43.9	76.6	96.7
Median BMP guideline % compliance	52.5	88.9	100	33	82.1	96.9
Min. BMP guideline % compliance	43	66.5	95	11	35.3	93
Max. BMP guideline % compliance	78.5	100	100	74.4	100	100

As stated previously, BMP implementation rates are sometimes used as a surrogate for BMP effectiveness. Alternatively, Christopher and Visser [73] proposed that the USLE-Forest erosion estimates could be used in place of BMP implementation inspection. However, BMP compliance inspections are widely used throughout the U.S. [59]. Therefore, we evaluated BMP audit implementation scores (% compliance) as the predictor for soil erosion estimates (Figure 4). The linear relationship was significant ($p \leqslant 0.0164$, $r^2 = 0.1357$), although the percentage of the variance explained was very low. Aberrant observations where low BMP audit scores were found to have low erosion rates were typically due to gentle terrain. Conversely, in a few situations, generally good BMP audit scores were linked to higher rates of erosion where BMP compliance was satisfactory, but stream crossing location and terrain features overwhelmed the BMP selected. We suspect that this relationship could be improved by revising some of the BMP audit questions to be more applicable to a specific stream crossing rather than an entire tract.

Figure 3. Representative photographs of the three BMP levels for the two crossing types.

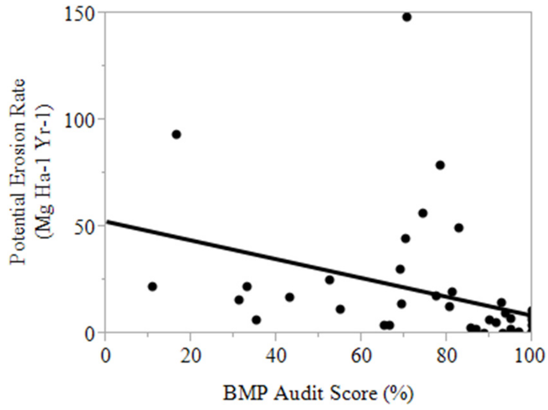

Figure 4. Linear relationship between the BMP audit score (%) and the potential erosion rate (Mg· ha^{-1}· year^{-1}) based on examination of 42 stream crossings in the Virginia Piedmont. (Potential erosion rate (Mg· ha^{-1}· year^{-1}) = 52.52 − 0.441 (BMP audit score %), *p*-value = 0.0164, r^2 = 0.1357).

Potential BMP upgrades and costs have been used regarding forestry BMPs by several researchers [89,90] in order to estimate costs. Overall, the two most common recommendations were to add additional water control structures or to increase soil cover. Such simple BMP improvements were hypothesized to reduce potential erosion rates from BMP− truck and skid trail crossings by approximately 5 times. The suggested improvements to upgrade the BMP-standard crossings to the BMP+ category could have important effects. The reduction for the truck roads would potentially reduce erosion by 11 times, and the skid trail enhanced BMPs would potentially result in a 6-fold decrease in erosion.

The data collected for assigning the BMP ratings allowed us to examine the types of water control and cover BMPs that were being used at the truck and skid stream crossing approaches (Table 5). The most common water control structures on the truck roads were water turnouts, which divert the water off the road without closing the road. Water bars were used on 45% of the roads, and water bars are expected on temporary roads. No water control structures were present on 5% of the truck road crossings. Gravel (65%) and some form of seed or mulch (70%) were the primary road cover BMPs used on the truck road stream crossings. Skid trails primarily used water bars for water control, because water bars are emphasized as an appropriate BMP in most BMP manuals. However, 50% of the skid trails had no water control structures; rather, 81.8% of skid trails used slash as a closure and water control treatment (81.8%). Seed and/or seed and mulch were used as cover BMPs on 31.9% of skid trails.

Table 5. Percentage of truck and skid trail stream crossings that use various water control or ground cover BMPs.

BMPs		Truck (%)	Skid (%)
Water Control BMPs	1. None	5	50
	2. Water bars	45	45.5
	3. Silt fence	15	0
	4. Straw bales	10	4.6
	5. Water turnouts	75	9.1
	6. Rolling dip	5	0
Ground Cover BMPs	1. None	10	4.6
	2. Slash	0	81.8
	3. Seeded grass	50	4.6
	4. Seeded grass and mulch	20	27.3
	5. Gravel	65	0

Costs of applying such hypothesized treatments are substantially more for truck roads than for skid trails, and the costs were greater to improve the BMP− roads and skid trails (Table 6). Average road improvement costs were between $400 and $500 per crossing, and skid trail improvements averaged between approximately $50 and $150 per crossing.

Table 6. Average potential erosion rates and erosion per crossing for truck and skid trail crossings before and after recommended BMP improvements.

Parameters Evaluated	Truck			Skid		
	BMP−	BMP-Standard	BMP+	BMP−	BMP-Standard	BMP+
Potential erosion rate before BMP upgrades (Mg· ha^{-1}· year^{-1})	40.1	8.8	3.1	56.9	12.0	2.0
Total potential erosion per crossing before BMP upgrades (Mg· crossing^{-1}· year^{-1})	0.6	0.3	0.1	2.1	0.2	0.02
Potential erosion rate following recommended BMP upgrades (Mg· ha^{-1}· year^{-1})	7.8	0.8	NA	10.6	2.0	NA
Total potential erosion per crossing recommended BMP upgrades (Mg· crossing^{-1}· year^{-1})	0.1	<0.1	NA	0.2	<0.1	NA
Average cost per crossing for BMP upgrades ($ crossing^{-1})	$451.34	$480.08	NA	$149.72	$44.94	NA

5. Discussion

Due to the expense and time required for paired watershed studies and in-stream evaluations of sediment following BMP applications, few studies have measured the actual efficiency of forest BMPs. Edwards and Williard [91] evaluated the literature and found only three studies that provided BMP efficiencies with regard to sediment loading reductions and reported BMP efficiencies ranging from 53%–94%. Rather than using in-stream water samples, numerous evaluations of BMPs have examined erosion, either through direct measurements or models. Five recent studies of bladed skid trails [75], overland skid trails [58], skidder stream crossing approaches [56], and truck road stream crossing approaches [16,19] in the Piedmont of Virginia have compared direct measures of sediment trap erosion with a variety of models. Overall, they found that the USLE-Forest provided rankings similar to those of direct measures of soil erosion, thus indicating that it is an appropriate tool for use by managers.

Another approach to evaluating the adequacy of BMPs is through examination of BMP compliance levels. Ice *et al.* [92] reported that western states implementing BMPs under the auspices of state forest practices acts were evaluating the effectiveness of the programs by monitoring compliance with the statutes. Sugden *et al.* [78] reported on the BMP progress made in Montana by reporting BMP compliance percentages. Schuler and Briggs [80] evaluated the effectiveness of New York's BMP program by reporting BMP compliance rates, and Briggs *et al.* [79] used a similar technique to evaluate the effectiveness of Maine's BMP program. Ice *et al.* [93] reported on BMP implementation rates across the U.S. and reported that the rates were widely used as surrogates for effectiveness.

Rather than use estimates of erosion or BMP compliance levels individually, we elected to use multiple evaluations regarding the quality of the BMP installations, including two variations of the VDOF BMPs (BMP audit scores and rankings based on BMP guidelines) and the USLE-Forest soil erosion model. Arguments can be made regarding the advantages of any one approach, but we believe the aggregation of three evaluation approaches provides strong evidence of BMP efficiencies.

The prevalent usage of culverts for truck roads and portable bridges for skid trails probably reflect the advantages of culverts for truck stream crossings and portable bridges for skid trail crossings from the loggers' perspective (Table 2). For log trucks, culverts are advantageous because they are relatively simple to install, can support heavier loads than many portable bridges, and require less knowledge of engineering compared to permanent bridges. In a survey of Virginia loggers, McKee *et al.* [65] found that portable steel or wooden bridges were commonly used by loggers for temporary skidder crossings (hence the alternative name of skidder bridge) because they can be used multiple times, thus having a reduced cost per crossing compared to culverts. However, culverts also have potential disadvantages. Improperly installed culverts can alter in-stream flow characteristics and potentially hinder migration of stream organisms [3,94,95]. Also, the installation of culverts requires that fill material be placed around the pipe in the streambed, which is why Reeves *et al.* [96] and Aust *et al.* [42] concluded that culverts may be associated with increased sediment levels compared to portable bridges.

Morris *et al.* [84] conducted a rainfall simulation experiment to determine the sediment contribution from a truck road culvert in the Virginia Piedmont that had substandard BMPs (BMP−), standard BMPs (BMP-standard) and enhanced BMPs (BMP+). BMP− produced 3.5 times more sediment than BMP-standard and 4.4 times more sediment than BMP+. Aust *et al.* [42] evaluated sediment above and below four types of operational stream crossings (portable bridges, culverts, fords, and pole crossings) and potential erosion rates for the associated stream crossing approaches in the Virginia Piedmont. Overall, they concluded that BMPs were an important factor for reducing sediment from all crossing types and that poorly designed and maintained approaches with insufficient BMPs could potentially produce up to 95 $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ of erosion. They also found that temporary bridge crossings tended to produce the least sediment, while culverts were associated with higher sediment levels. Permanent crossings tended to produce more sediment than temporary crossings, because temporary crossings were effectively closed with BMPs and temporary roads disturbed smaller areas within SMZs.

Continued reliance on culverts for truck road stream crossings would benefit from enhanced BMPs, and our data emphasize that culverts are still being used and that BMP implementations can be improved for these situations. Our predicted enhancement of BMP− truck road crossings to BMP-standard level would potentially reduce erosion rates by 5.1 times, and we estimated the average cost of these improvements to be approximately $450 (Table 6). Improving a BMP-standard crossing to BMP+ levels would reduce erosion by 11 times, and predicted erosion rates would drop to less than 1 $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$, which is similar to erosion rates in undisturbed forests [7]. Costs for these improvements would be between $450 and $500 per crossing. These BMP enhancements provide dramatic evidence of the potential positive effects of BMPs for a relatively small cost per crossing, compared to a shift to permanent bridges.

Truck crossings had higher mean and median BMP audit scores (85.4% and 91.4%, respectively) compared to the mean and median BMP audit scores for the skidder stream crossings (70.8% and 77.8%, respectively) (Table 3). For the same general period, the VDOF 2014 BMP audit report provided a somewhat similar mean BMP audit score (89.2% overall) for both truck and skid trail stream crossings in the central region. Our BMP audit scores could have been lower than the VDOF audit for several reasons. The VDOF evaluations cover the entire harvest site, whereas we were applying the questions to one particular crossing. Also, we conducted our audit on sites that were harvested from January through April, which was a very wet season and could have affected BMP performance.

In this particular study, we also suggest that our estimates of soil erosion are nearly equivalent to the sediment delivery to the stream. Lang *et al.* [43] examined SMZ failures in the Piedmont and found that stream crossings are their primary cause. In a separate study, Lang *et al.* [74] compared USLE erosion estimates from forest road stream crossing approaches in the Piedmont of Virginia and found that sediment delivery rates from forest approaches to streams were nearly 100%. Rivenbark and Jackson [44] examined causes of SMZ failures in the Piedmont and concluded that roads and stream crossings were directly associated with 25% of all SMZ failures. Thus, our USLE-Forest estimates potentially provide the approximate quantity of sediment delivery that could be expected at these crossings. This higher sediment delivery at stream crossings is markedly different than most forest operations, where sediment delivery would be far less than potential erosion rates. Ward and Jackson [97] compared soil erosion below timber-harvested and site-prepared sites in the Piedmont with the USLE and sediment traps at the SMZs, and estimated a sediment delivery ratio of 25% to the edge of the SMZ. They found that the SMZ trapped 71%–99% of the erosion before delivery to the stream. Lakel *et al.* [98] did a comparable study below harvested sites without site preparation and found a sediment delivery ratio between 3% and 14%, but Lakel also emphasized that BMP failures and resultant sediment problems were potentially much higher at stream crossings. It is important to understand that roads may provide a more direct conduit to the stream.

In our study, the differences in erosion between the truck roads and skid trail stream crossings were not unanticipated, as skid trails have lower BMP standards than truck roads. For example, truck road stream approaches have a recommended slope of ⩽10%, whereas bladed and dispersed overland skid trails may have slopes of ⩽25% and ⩽35%, respectively, and still comply with the VDOF BMP guidelines [71]. The steeper approaches allowed on the skid trail stream crossings are a contributing factor to the twofold potential erosion rate of the skid *vs.* truck crossing (Table 3), and another future BMP enhancement for skid trail stream crossings could be to generally keep skid trail approaches ⩽15%, although this may not always be feasible.

The third surrogate for road crossings and quality of BMPs involved evaluation of the road template, road drainage structure, road cover BMPs, and stream crossing structure in order to develop a general ranking of the crossing and approach (Table 4). Subsequently, we recommended BMP upgrades that would allow the BMP− and BMP-standard categories to move to the next higher BMP category and estimated the potential erosion for each crossing using the USLE-Forest (Table 6). Such hypothesized improvements and costs have been used regarding forestry BMPs by several researchers [89,90] in order to estimate costs.

For BMP− situations, inadequate water control features were the most common BMP implementation problem for both skid trails and truck roads. The most prevalent water control on BMP− skid trails related to water bars with inadequate spacing based on the slope of the skid trail or ineffective construction. Reasons for water control inadequacies are uncertain, but equipment operators who visually estimate requirements with little measurement often are responsible for placement of water control structures. Poorly designed turnouts that were too small or led the water directly towards the stream were common reasons for turnout failures on BMP− truck roads. Coverage problems for BMP− roads typically involved either inadequate or no gravel, and poor establishment of seeded grass. BMP− skid trails that had problems with slash coverage were often related to the use of slash that was too large to provide good soil contact or was too sparse. For BMP− skid trails using seed, the problems for cover typically related to lack of grass establishment.

The two most common recommendations were to add additional water control structures or to increase surface cover. Such simple BMP improvements were estimated to reduce potential erosion from BMP− truck and skid trail crossings by five times (Table 6). The improvements for the BMP-standard crossinigs suggested upgrading these to the BMP+ category with similar positive effects. The reduction for the truck roads would potentially reduce erosion by 11-fold, and the skid trail enhanced BMPs would potentially result in a 6-fold decrease in erosion. These reduction levels compare favorably to the reduction levels measured by Wade *et al.* [57], who found that enhanced ground cover on bladed skid trails could reduce erosion by 30 times, and the road crossing studies by Brown *et al.* [16,19], who reported that increased levels of BMPs could reduce road erosion rates by 7.5 to10 times. As expected, the average BMP audit scores improved for both truck and skid trail crossings as they progressed from BMP− to BMP-standard to BMP+. Morris *et al.* [84] used a similar methodology for evaluating the sediment contributions of different stream crossings in the Piedmont (ford, culvert, bridge) having three levels of BMP implementation. They evaluated total sediment loading for one year, and overall contributions were 98.5 Mg for BMP−, 28.5 Mg for BMP, and 22.5 Mg for BMP+. Our findings also emphasize the importance BMPs at stream crossings and the potential benefits of using more than the standard level of BMP for such critical areas. The Virginia Department of Forestry has estimated that approximately 1000 new stream crossings are constructed annually, and improved BMP compliance at these crossings provides obvious opportunities for sediment reduction.

After completing the Virginia BMP guideline rankings, we evaluated the specific BMPs needed for enhancement of existing BMPs and estimated the cost of the recommended BMP improvements using the Virginia Tech Road and Skid Trail Cost Method [85]. Costs of applying hypothesized treatments to upgrade BMP levels were substantially more for truck roads than for skid trails, and the costs were greater to improve the BMP− roads and skid trails (Table 4). Average road improvement costs were between $450 and $580 per crossing, and skid trail improvements ranged between approximately $50 and $150 per crossing. McKee *et al.* [65] conducted interviews with 70 Virginia loggers and found that the estimated costs for stream crossing closure BMPs in the Piedmont was $445 in 2009. Our costs for improvement are greater than the estimated costs in 2009, but our evaluations entailed a careful assessment of each site rather than relying on loggers' recollections. Our estimates were based on remedial BMPs, which would have been less cost-efficient than if completed during the original BMP installations. Furthermore, our hypothesized recommendations would not include any substandard BMPs that might have been included in previous estimates.

6. Conclusions

1. Skid trail stream crossings have lower BMP audit scores and greater potential soil erosion rates than truck road stream crossings. We recommend that BMP guidelines emphasize the use of lower skid trail slopes where practical, perhaps $\leqslant$15%, for skidder stream crossing approaches, and emphasize slash for stabilizing bare soil areas at temporary approaches.
2. The three indices of BMP efficacy (potential soil erosion, BMP audit compliance percentage, and BMP guideline categorizations) unanimously indicate that skid trail stream crossings have lower BMP implementation. Furthermore, cost estimates indicate that closure BMP for skid trails are much cheaper than for truck roads; therefore, we recommend that skid trail closure BMPs receive higher attention. This appears justified both from an environmental perspective and from expenditure effectiveness.
3. BMP-standard and BMP+ stream crossings clearly minimize the potential erosion and sedimentation relative to BMP− stream crossings. The higher levels of potential erosion and sediment associated with BMP− stream crossings indicate that specific problem sites are potentially worth remedial action even after site closure.
4. Although our multi-faceted approach to BMP evaluation is too time-consuming for most state agency applications, we feel that it would be appropriate for research evaluations in other regions or for subset audits within a given state.
5. Although truck crossings generally had higher levels of BMP implementation, addition of BMP+ at truck crossings had substantial payoff in terms of potential erosion control.

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